# High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields

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Award Number: N00014-08-1-0610
http://www.mit.edu/~vfrl/

## LONG-TERM GOAL

Given remote and direct physical measurements of a realistic ocean wavefield, obtain a high-resolution description of the wavefield by integrating the measurements with direct phase-resolved wave computations including realistic environmental effects such as wind forcing and wave breaking dissipation. Inform and guide the measurements necessary for achieving this reconstruction and address the validity, accuracy and limitations of such wavefield reconstructions.

## OBJECTIVES

The specific scientific and technical objectives are to obtain:

1. Development of a phase-resolved, deterministic prediction capability for nonlinear wavefield reconstruction and evolution at intermediate scale (O(1) ~ O(10)km) using ship-mounted radar wave measurements
2. Incorporation and evaluation of physics-based wind-forcing and wave-breaking models that are developed/calibrated/validated based on simulations and measurements
3. Characterization and quantification of uncertainty and incompleteness in sensing data on wavefield prediction
4. Direct comparison between quantitative field/laboratory measurements and nonlinear wavefield reconstruction and prediction

# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



| | | |
|---|---|---|
| 1. REPORT DATE<br>**2009** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2009 to 00-00-2009** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**High-Resolution Measurement-Based Phase-Resolved Prediction of Ocean Wavefields** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Massachusetts Institute of Technology,Center for Ocean Engineering,Department of Mechanical Engineering,Cambridge,MA,02139** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **6** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

5. Development of a theoretical/computational framework for wavefield reconstruction and predictability that can guide deployment of wave sensing systems and data interpretation

## APPROACH

We develop and apply a comprehensive deterministic model for intermediate scale, O(10)km, wave environment prediction by integrating whole-field and multiple-point direct measurements of the wave and atmospheric environment with nonlinear simulation-based reconstruction of the wavefield. The wave reconstruction is based on phase-resolved simulation of nonlinear surface wave dynamics, and utilizes hybrid (from different types of sensors) measurements that may contain noise, uncertainty and gaps. The simulations also incorporate physics-based wind forcing and wave-breaking dissipation models, which are themselves developed/validated/calibrated based on measurements.

Nonlinear wavefield reconstruction is based on an iterative optimization approach using multilevel phase-resolved wave models of different nonlinearity orders. Specifically, for low-level optimization which is sufficient for mild waves, the theoretical linear and second-order Stokes solutions are used. For high-level optimization which is required for moderately steep waves, an efficient nonlinear wave simulation model based on the high-order spectral method is employed. Once the wavefield is reconstructed, its future evolution is given by wave models using the reconstructed wavefield as an initial condition (Wu 2004; Yue 2008). In wave modeling, wind forcing is included through a pressure distribution on the free surface and wave-breaking dissipation is considered by an effective low-pass filter in spectral space. Other physical effects such as those due to the presence of current and finite depth can also be directly considered in wave modeling.

## WORK COMPLETED

We focus on the development and improvement of the deterministic nonlinear wave reconstruction capability based on radar sensed wave data and performance tests of the capability using measurement of realistic ocean waves. Specifically, the following work is completed:

- **Development of high-resolution wave reconstruction and prediction capability:** We extend the reconstruction and forecasting capability for discrete point wave data to the situation with whole-field radar sensed wave data. The effects of current and finite depth are also included. In particular, we focus on the understanding of wavefield's predictability (in spatial-temporal domain) based on given radar sensed wave data.

- **Modeling of wind input:** To account for wind effects in wave reconstruction/prediction, we develop and validate a first generation modeling of wind forcing for direct phase-resolved nonlinear wavefield simulations. In this model, the wind forcing is modeled as a pressure distribution closely correlated to the wave slope. The effectiveness and parameterization of the model is investigated by comparisons to existing laboratory/field observations.

- **Validation and calibration with field measurement:** The developed wave reconstruction capability is applied to realistic ocean waves using (WAMOS) radar sensed wave data. The performance of the reconstruction capability is validated and evaluated.

## RESULTS

The preliminary applications of the developed wave reconstruction and prediction capability indicate that the realistic ocean wavefield evolution can be deterministically reconstructed and forecasted based on WAMOS sensed wave data. A sample result is described below.

The site of the wavefield considered is at LAT 54°00.53N, LONG 06°35.16W, Norway. WAMOS radar sensed wave data (in Nov. 2008) is used for this application. The sea condition is mild with a significant wave height of $H_s$ ~ 3.53 m and a peak wave period of $T_p$ ~ 7.11s. The wavefield has a relatively small spreading angle. We reconstruct the wavefield in a domain $D$ of ~1km × 1km based on radar sensed wave data at an instant, say, $t = 0$, and then predict its evolution in a short period of time, $t \in [0, 4T_p]$. Figure 1 shows the comparisons of the reconstructed phase-resolved wavefield with the radar sensed data at $t = 0$ (which is used in reconstruction), and the predicted wavefields at $t = 2\mathrm{T_p}$, $4\mathrm{T_p}$ wit the radar sensed data (which are not used in reconstruction). The comparisons indicate that the key phase-resolved structures of the wavefield are all properly reconstructed and predicted.

Figure 2 shows the (point-to-point) discrepancy in the wave elevation (normalized by the significant wave amplitude) between the reconstructed/predicted wavefield and the original radar sensed wave data at $t/T_p$ = 0, 1, 3 and 4. The error in the predicted wavefield increases with time, especially in the region near the upstream boundary of the original domain. Figure 3 shows the variation of the correlation coefficient (relating the reconstructed/predicted wavefield to original radar sensed wave data) with time. The result indicates that the correlation coefficient computed with waves in the predictable region decreases much slower than that computed with waves in the original fixed domain. The predictable region, which is determined by the properties of the wavefield, varies in space with time for a given initial sensed wave data.

## IMPACT/APPLICATIONS

Advances in large-scale nonlinear wave simulations and ocean wave sensing have recently made it possible to obtain phase-resolved high-resolution reconstruction and forecast of nonlinear ocean wavefields based on direct sensing of the waves. Such a capability will significantly improve ocean-surface sensing measurements and deployment, and data assimilation and interpretation, by providing a comprehensive wave-resolved computational framework. Another important potential application of this is to greatly increase the operational envelopes and survivability of naval ships by integration of such capability with ship-motion prediction and control tools.

## RELATED PROJECTS

The present project is related to the project entitled "Phase-Resolved Reconstruction and Forecast of Ocean Wavefields Using Scanning-Sensing Wave Measurements" (N00014-08-1-0694). The present project focuses on the application of the deterministic wave reconstruction/prediction capability to realistic ocean environment while the related project focuses on the understanding of fundamental algorithms and accuracies/reliabilities of deterministic wave reconstruction and forecasting based on point and/or whole field wave measurements.

## REFERENCES


1. Wu, G. 2004 Direct simulation and deterministic prediction of large-scale nonlinear ocean wave-field. Ph.D Thesis, Massachusetts Institute of Technology, Cambridge, MA.


## PUBLICATIONS


1. Yue, D.K.P. 2008 Nonlinear Wave Environments for Ship Motion Analysis, *27th Symposium on Naval Hydrodynamics*, October 5 – October 10, 2008, Seoul, Korea [published]

2. Xiao, W., Liu, Y. and Yue, D.K.P. 2009 Ocean Wave Prediction Using Large-Scale Phase-Resolved Computations, *Proceedings of the DoD HPCMP Users Group Conference* 2009, June, San Diego, CA [published]

3. Wu, G., Liu, Y., Kim, M.H. and Yue, D.K.P., 2008 Deterministic reconstruction and forecasting of nonlinear irregular wave fields. *J. of Fluid Mech*. [submitted].

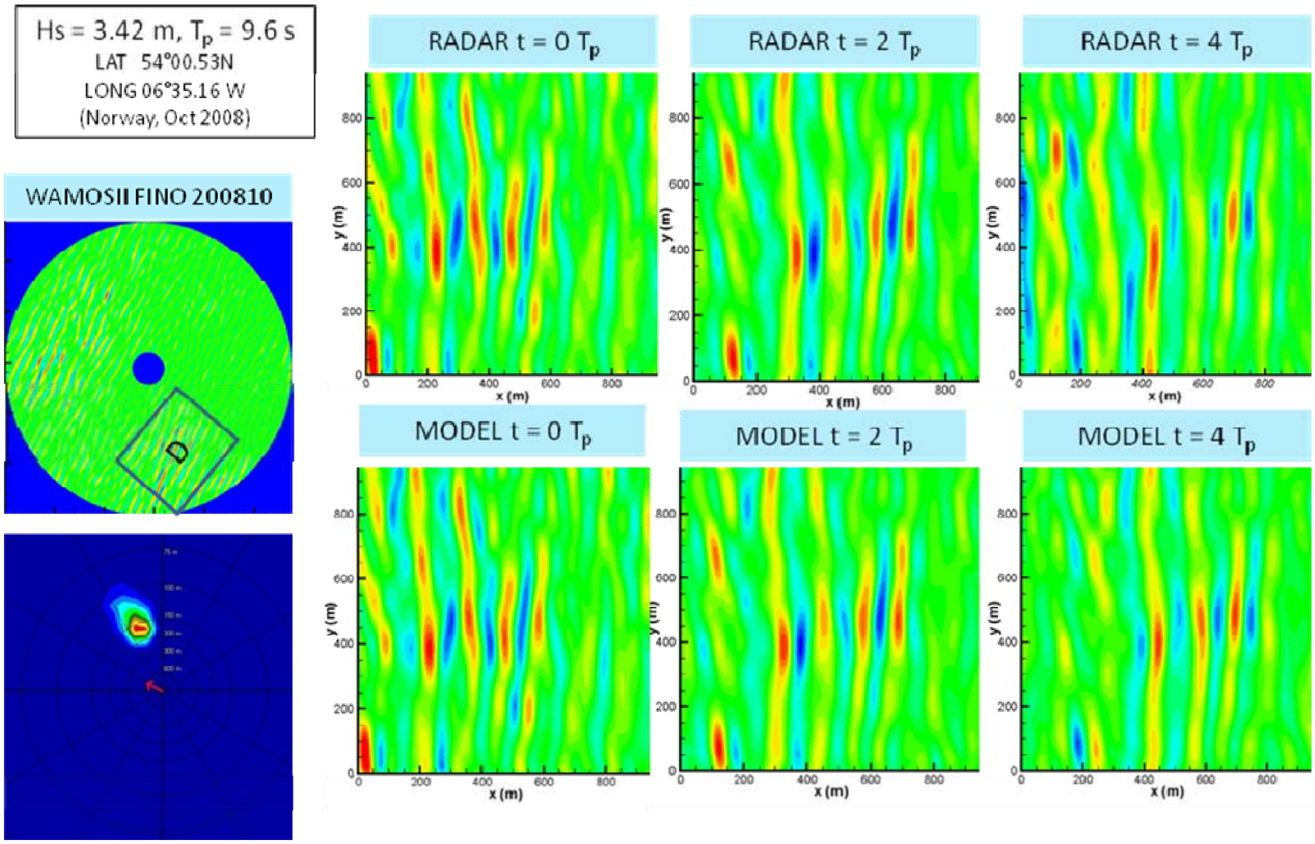


***Figure 1: Comparison of reconstructed/predicted wavefields (bottom) and radar sensed wavefields (top). The far left figures represent sample radar inversion wavefield (top) and the wavenumber spectrum of the sensed wavefield (bottom).***

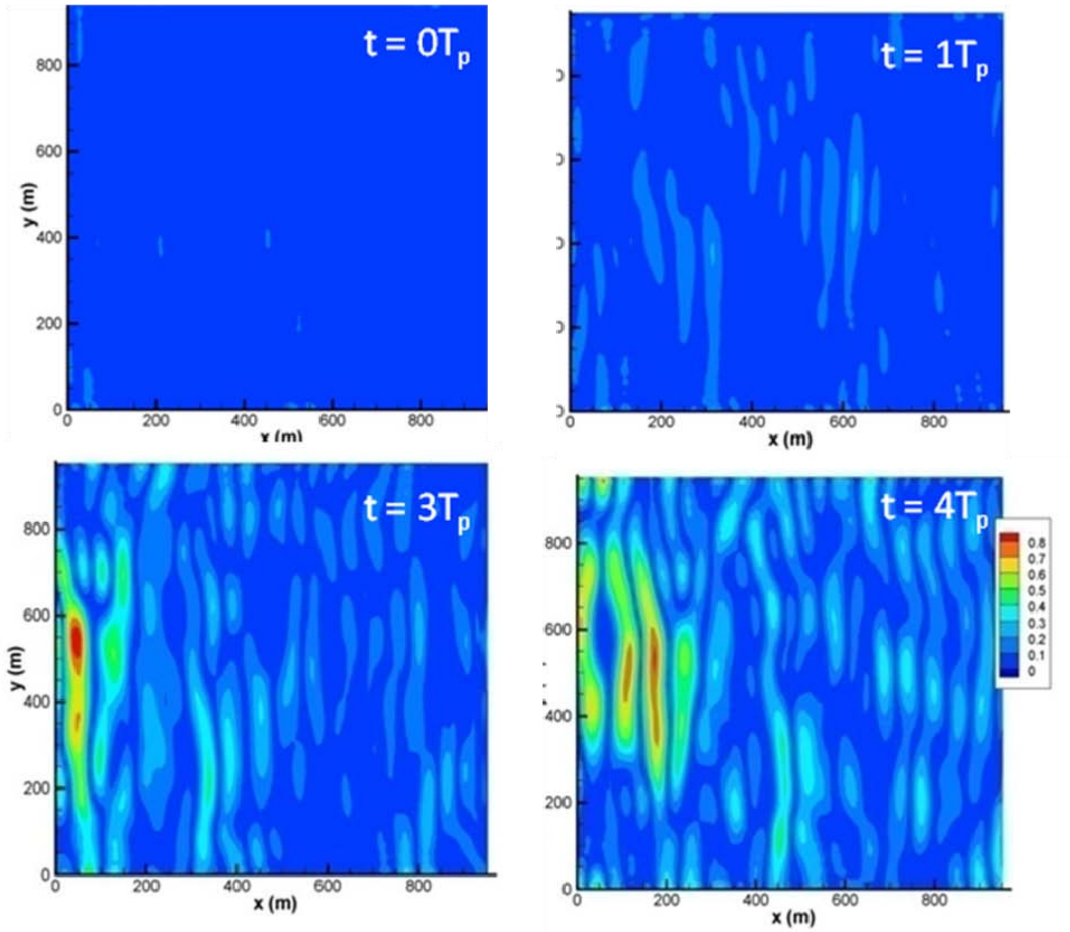


***Figure 2: Distribution of the discrepancy (normalized by the significant wave amplitude) between the reconstructed/predicted wavefield and the original radar sensed wavefield data at four instants $t/T_p$ = 0, 1, 3, and 4. The radar sensed wave data at $t/T_p$ = 0 is used in reconstruction while that at other times is not used in prediction.***

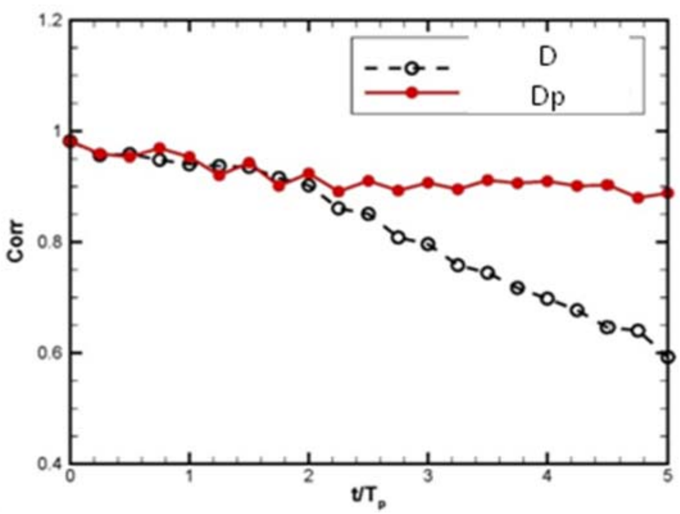


***Figure 3: Time variation of correlation coefficients between the predicted wavefield and the radar sensed wave data. The correlation coefficients are computed using waves in the predictable region (red line), and in the original domain (black line).***